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# TOPLine: a Delay-Pole-Residue Method for the Simulation of Lossy and Dispersive Interconnects

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**Abstract:** This paper presents a modeling technique for lossy frequency-dependent multiconductor transmission lines. The main algorithm involves rational approximations combined with modal delay extraction. The transient results obtained for three benchmark cases are reported and compared to reference solutions.

## 1 Introduction

Electrical interconnects at chip, multichip, package, and board level constitute one of the most critical parts for the signal integrity of all electronic systems. Nonetheless, an accurate and efficient transient simulation of electrical interconnects is still a challenging task even in the most advanced circuit solvers. This is due to the intrinsic difficulties in the design of stable algorithms for the time-domain analysis of structures with frequency-dependent parameters. Indeed, it is well known that accurate interconnect models must take into account skin effect losses and dielectric losses. The underlying physics is best captured using a frequency-domain approach, leading to constitutive parameters with a complex dependence on frequency.

This paper presents a technique for the transient analysis of multiconductor transmission lines with frequency-dependent per-unit-length parameters. The key features of the main algorithm are delay extraction and rational approximation. Delay extraction allows the analysis of interconnects with arbitrary length  $\mathcal{L}$  and leads to the definition of suitable delayless transfer functions of the lines. These are approximated by rational functions, which are then used to synthesize SPICE-ready equivalent circuits. The very high accuracy of the method is documented by presenting the simulation results for the three benchmark cases detailed in [1]. A short description of the method and the transient waveforms are given below.

## 2 Modeling algorithm and numerical results

We consider a multiconductor transmission line governed by the telegraphers equations

$$\begin{aligned} -\frac{d}{dz} \mathbf{V}(z, j\omega) &= [\mathbf{R}(j\omega) + j\omega \mathbf{L}(j\omega)] \mathbf{I}(z, j\omega), \\ -\frac{d}{dz} \mathbf{I}(z, j\omega) &= [\mathbf{G}(j\omega) + j\omega \mathbf{C}(j\omega)] \mathbf{V}(z, j\omega), \end{aligned}$$

where all constitutive parameters are frequency-dependent. Frequency tables of inductance, capacitance, resistance, and conductance matrices as in [1] are the raw data describing the line. The common background of most advanced algorithms for the transient analysis of this structure is the derivation of rational approximations for some suitable transfer functions. In fact, a rational approximation can be easily transformed into an equivalent circuit to be used either in time or frequency domain. The success in terms of accuracy and efficiency depends on the suitability of the approximation with respect to the specific target function to be approximated. We have obtained excellent results [2] by defining the target functions for the approximation to be the characteristic admittance and the delayless propagation operator, defined as

$$\begin{aligned} \mathbf{Y}_c(s) &= \left( \sqrt{\mathbf{Y}(s)\mathbf{Z}(s)} \right)^{-1} \mathbf{Y}(s) \\ \mathbf{P}(s) &= \mathbf{M}_\infty^{-1} \exp \left\{ -\mathcal{L} \sqrt{\mathbf{Y}(s)\mathbf{Z}(s)} \right\} \mathbf{M}_\infty \text{diag} \{ e^{sT_k} \}, \end{aligned}$$

where  $\mathbf{Y}(s) = \mathbf{G}(s) + s \mathbf{C}(s)$ ,  $\mathbf{Z}(s) = \mathbf{R}(s) + s \mathbf{L}(s)$ , and where  $\mathbf{M}_\infty$  is the modal decomposition matrix at  $s = \infty$ . The modal delays are  $T_k$ . The above matrix functions have bounded and smooth elements when evaluated for  $s = j\omega$ . In addition, their asymptotic values for low and high frequencies are easily computed. For this reason, we explicitly enforce these asymptotic constraints during the generation of the rational approximations. This allows the control of out-of-band behavior of the approximation, leading to a well-behaved model throughout the frequency axis.

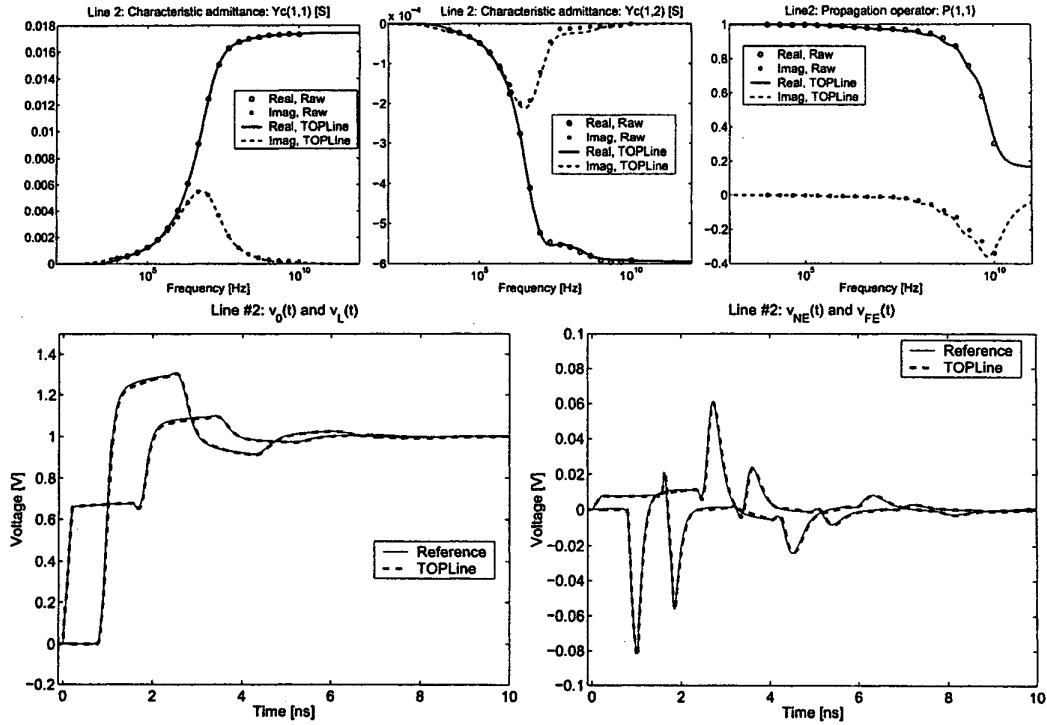


Figure 1: Line 2: Rational approximation of characteristic admittance and propagation operator elements (top panels); voltages at the terminations of active line (bottom left) and crosstalk voltages (bottom right).

The rational approximation algorithm is based on an iterative procedure that automatically determines the location of the poles in order to achieve a target accuracy in the rational fit. All poles are real and are constrained to a frequency band that is automatically determined from the input dataset. At each iteration the set of poles is known and the corresponding residues are computed via linear least-squares. If the resulting accuracy is not sufficient, one pole is added for next iteration. The location of this new pole is computed by attempting to place it where the reduction in the fitting error is most likely. The passivity for the resulting rational models cannot be proved a priori. However, no passivity violation ever occurred in the large number of tests that we performed on several cases.

Once the rational approximation is found for both  $Y_c(s)$  and  $P(s)$ , the poles/residues are used to synthesize an equivalent circuit for direct inclusion in a standard circuit solver. This subcircuit is made of resistors, capacitors, and dependent sources. In addition, scalar lossless transmission lines are used to synthesize the modal delays. The current version of the algorithm has been implemented as an external device in PowerSPICE using the dedicated Application Program Interface. This is mainly a software environment allowing the direct integration between the main PowerSPICE kernel and external circuits or devices specified in a dedicated user-written code.

In order to compare the accuracy of the proposed technique we have produced a reference solution for all benchmark cases detailed in [1]. This is possible since all terminations are linear. Therefore, a standard frequency-domain solution is computed and inverse FFT is used to recover the transient waveforms excited at the line terminations. The plots in Figures 1–4 report both the rational approximations and the transient waveforms compared to the reference solution. All relevant waveforms for Lines 2–4–6 are reported, using the acronym 'TOPLine' (TORino Polytechnic Line) to identify the proposed technique. Almost no difference can be noticed in all cases. This confirms the excellent behavior of the proposed method in terms of accuracy. The runtime required for transient analysis on a Linux PC with a Pentium IV CPU 1.8 GHz is 1.35 seconds for Line 2, 4.4 seconds for Line 4, and about 7 seconds (independently on the line length) for Line 6. As a conclusion, we can say that the proposed algorithm with an efficient implementation leads to an appropriate combination of accuracy/timing for extensive use in the design stage of interconnected systems.

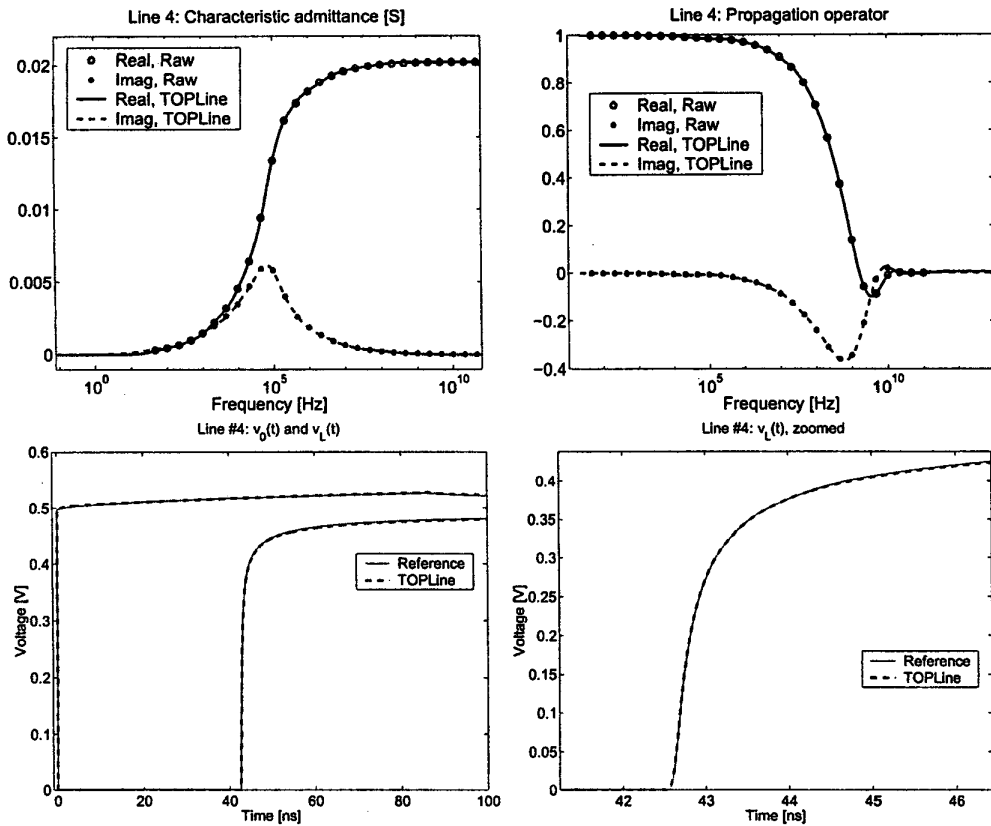


Figure 2: Line 4: Rational approximation of characteristic admittance (top left) and propagation operator (top right). Near and far terminations voltages (bottom panels).

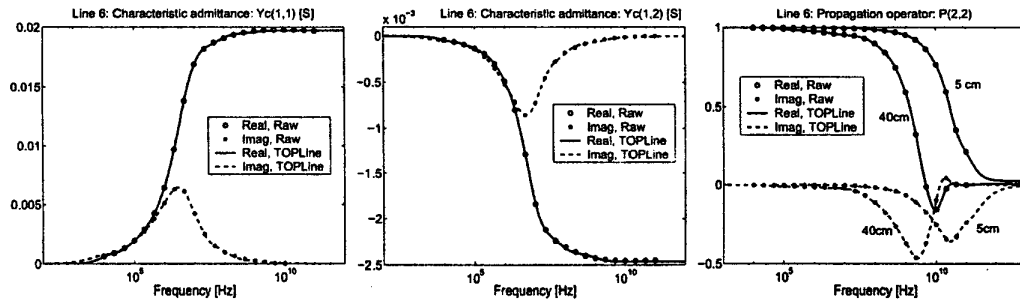


Figure 3: Line 6: Rational approximation of characteristic admittance and propagation operator elements.

## References

- [1] A. E. Ruehli, A. C. Cangellaris, H.-M. Huang, "Three test problems for the comparison of lossy transmission line algorithms," this volume.
- [2] S. Grivet-Talocia, F. Canavero, and I. Maio, "Recent advances in reduced-order modeling of complex interconnects," in *IEEE 10<sup>th</sup> Topical meeting on Electrical Performance of Electronic Packaging, Cambridge, Massachusetts, USA*, pp. 243–246, October 28–31, 2001.

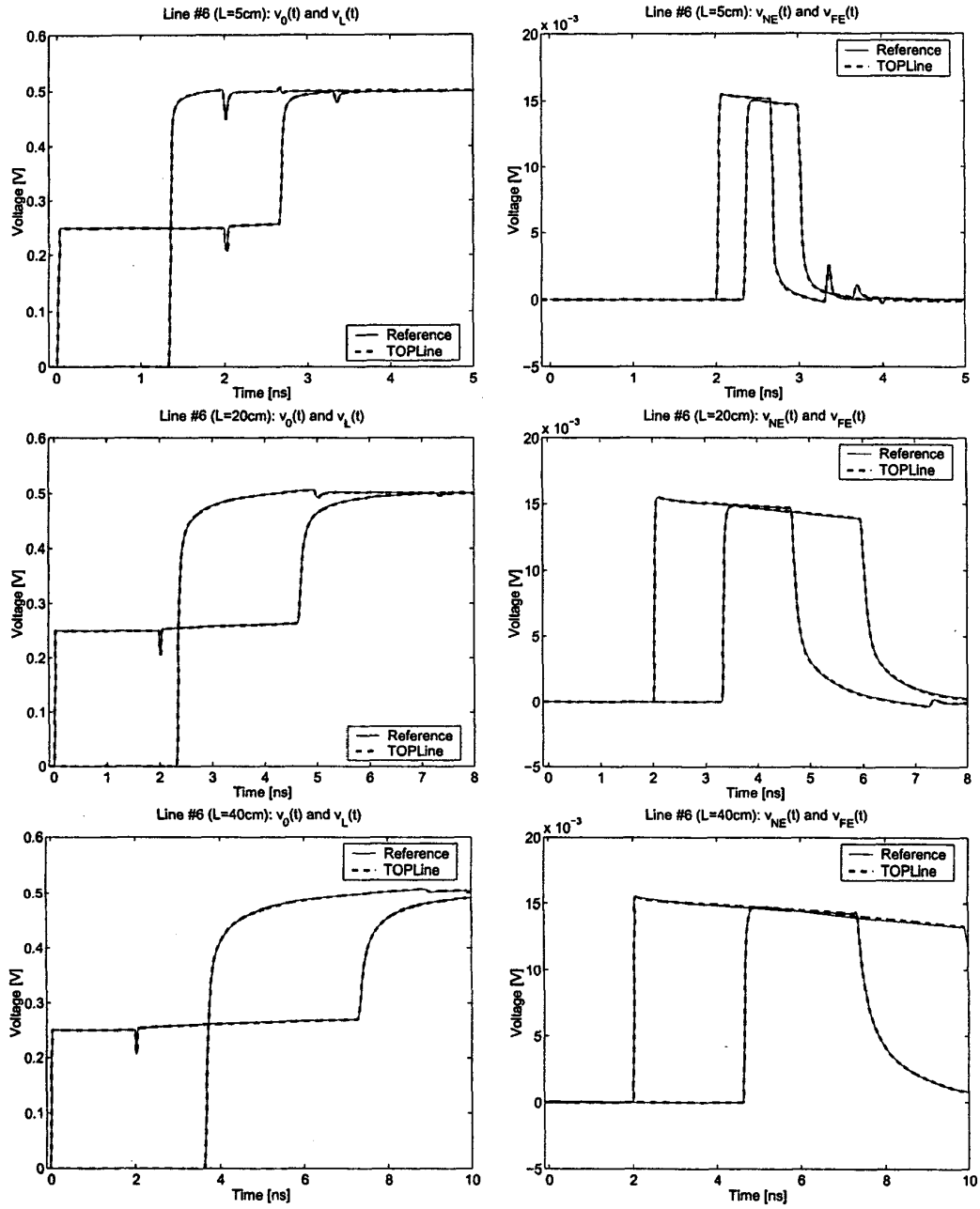


Figure 4: Line 6: Voltages at the terminations of active line (left) and crosstalk voltages (right) for line lengths  $\mathcal{L} = 5$  cm (top),  $\mathcal{L} = 20$  cm (middle), and  $\mathcal{L} = 40$  cm (bottom).